Spectroscopic Ellipsometry
Room 116 - Session EL1-ThA

Fundamental Ellipsometry Applications

Moderators: Tino Hofmann, University of North Carolina at Charlotte, **Megan Stokey**, Milwaukee School of Engineering

2:15pm **EL1-ThA-1 Mueller Matrix Ellipsometry for Optical Metasurfaces***, **Morten Kildemo,*** Department of Physics; NTNU;Norway **INVITED**

We review our recent works using spectroscopic Mueller Matrix Ellipsometry together with full wave modeling that has allowed on one hand to reveal new physics of optical plasmonic or dielectric metasurfaces [1-4], and on the other hand achieve high control of the manufactured metasurfaces. Furthermore, as metasurfaces are at the brink of a commercial breakthrough, we aim at showing that it is likely that this transition will be facilitated through the appropriate use of spectroscopic ellipsometry.

In part one of this talk, we discuss the physics of the full wave models of plasmonic metasurfaces realized from Mueller Matrix Ellipsometry, and in particular address the MME metrology of arrays of Au patches supporting both Gap Surface Plasmons and Surface Plasmon Polaritons[2,3]. A plane wave expansion of the field in the insulator shows that the fundamental localized resonances are composed of oppositely propagating modes, and we produce evidence that the sharp dispersive resonances observed in p-polarization, excited near the opening of diffracted orders, are grating coupled SPPs.

In part two, we discuss our recent work on design, manufacturing and a complete characterization of a class of optical metasurfaces: polarization beam splitting metasurfaces [4]. We describe our recently developed methodology using diffractive mode Mueller matrix spectroscopic ellipsometry (MMSE). Hence, we study both experimentally (and thereby with more conviction also numerically), how well these metasurfaces work in practice. In particular, we show that through appropriate control of the optical properties using MMSE, and feedback to both the nano-manufacture and design step, that we reach accurate and reproducible meta-surfaces. It is recalled that meta-surfaces are based on well-designed nano-resonators (in our case a-Si:H) that are manufactured on a plane interface.

References.

[1] P. M. Walmsness, T. Brakstad, B. B. Svendsen, J. P. Banon, J. C. Walmsley and M. Kildemo, JOSA B 36 (2019): E78-E87.

[2] P. M. Walmsness, N. Hale and M. Kildemo (2021). JOSA B 38 (2021): 2551-2561.

[3] P. M. Walmsness, N. Hale and M. Kildemo Opt. Lett. (2021) (in press).

[4] V. M. Bjelland, N. Hale, N. Schwarz, D. Vala, J. Høvik, and M. Kildemo, Opt. Express 32, 703-721 (2024).

2:45pm **EL1-ThA-3 The Wealth of Information Delivered by Spectroscopic Imaging Ellipsometry***, **Kurt Hingerl,** C. Cobet,* University Linz, Austria*; M. Schiek,* Physikalisch-Technische Bundesanstalt Braunschweig, Germany

Spectroscopic ellipsometry is a non-invasive and non-destructive measurement technique, and can allow a user to determine several film properties simultaneously. The technique is fast and requires no sample preparation. It is also precise, reproducible, very sensitive to thin films even thinner than 1 nm. In the last 10 years commercial imaging ellipsometers have been developed combining these advantages with (almost) diffraction limited imaging systems[1]. Using spectroscopic imaging ellipsometry (SIE)-now allows in addition to vertical sample structure determination to gather a huge variety of in-plane information on geometry and material, especially when combined with fast numerical Maxwell solvers.

First it will be discussed, which information can be delivered by SIE for nanostructured samples with inner boundaries. The major rule remains the same: the continuity conditions for the tangential components of the electric and magnetic field, as well as for the normal components of the displacement field and the magnetic flux have to be fulfilled also at inner, non stratified boundaries. In the contribution it will be first discussed, how ellipsometric measurements with an imaging ellipsometer shall be interpretedin the case of no depolarization and with depolarization. As an example, Au patches with an extension of 50 x 50 nm^2 and 10 nm height on Si can be easily detected by SIE, provided the two ellipsometric angles ψ and Δ are measured with an accuracy of 0.01°. This result proves that the well known sensitivity of ellipsometry on the thickness of overlayers can be extended also to the in-plane dimensions[2,3]. Finally comparative measurements with electron microscopes will be presented, which show the potential for optical, nondestructive, and production line compatible defect analysis.

References:

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[2] J. P. Perin and K. Hingerl, Appl. Surf.Sci., **421**, 761 (2017)

[3] K. Hingerl, Jour. Appl. Phys. **129**, 113101 (2021)

3:00pm **EL1-ThA-4 In-Situ Optical Investigation of Electrochemically Controlled Surfaces and Thin Films***, **Christoph Cobet,** L. Rosillo Orozco,* Johannes Kepler University, Austria*; S. Vazquez-Miranda,* ELI Beamlines Facility, Czechia*; K. Hingerl,* Johannes Kepler University, Austria

The applied electrical potential between an electrolyte and a solid electrode, whether it is a metal, semiconductor, polymer or a bio-membrane, could initiate versatile surface or film modifications. First of all, the potential simply redistribute charges. But in the new thermodynamic equilibrium adsorbates or even the conformational appearance could change and thus determine the catalytic efficiency of an electrode material, for example. From an experimental point of view, the interfacial electric potential is, on the other hand, a very precise and powerful tool to manipulate thermodynamic equilibrium conditions. It can be modified over a huge range of several eV. Similar effects are otherwise only possible with extreme e.g. temperatures or pressures. However, the fundamental knowledge about the atomic structure and the related processes is still relatively limited compared to classical surface science in vacuum. The reasons are theoretical challenges in the description but primarily experimental limitations as electron based methods like XPS are not applicable at solid-liquid interfaces. Motivated by the increasing interests in this topic, we have started to use optical polarization methods such as spectroscopic ellipsometry (SE) and reflection anisotropy spectroscopy (RAS) to obtain new and complementary in-situ information. From experiments in vacuum or gas phase environment it is known that these methods could provide an exceptional surface sensitivity. This sensitivity allows us to observe the formation of surface quantum well states at a metal-electrolyte interface or an in-situ determination of the electronic band banding at semiconductor surfaces like the polar ZnO [0001] and [000-1] surface.

3:15pm **EL1-ThA-5 Thz Electron Paramagnetic Resonance Generalized Spectroscopic Ellipsometry, Bloch Equations and Superconvergence Rules in the Frequency-Dependent Magnetic Susceptibility***, **Mathias Schubert,*** University of Nebraska-Lincoln, USA*; V. Rindert, V. Darakchieva,* Lund University, Sweden

A new optical technique is presented to detect the signatures of electron paramagnetic resonances in materials at terahertz frequencies and high magnetic fields using generalized spectroscopic ellipsometry.[1] Measurements dispense with the need for modulation techniques and resonance cavities.[1] The elements of the normalized Mueller matrix are determined, which contain hitherto undetected information about the polarization, frequency, and field response of unpaired electron spin moments including nuclear magnetic coupling.[1,2] Approaches to model analysis of the frequency dependent magnetic susceptibility tensor are discussed, Bloch equations are revisited, and an analogue to the Lyddane-Sachs-Teller relationship is shown from theory and experiment.[3,4] Examples include quantification of the defect properties of Fe and Cr in Ga_2O_3, N in 4H-SiC, and Fe in GaN.

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[2] Editors Highlights, High-field/high-frequency electron spin resonances of Fe-doped β-Ga2O3 by terahertz generalized ellipsometry: Monoclinic symmetry effects, Steffen Richter, Sean Knight, Oscar Bulancea-Lindvall, Sai Mu, Philipp Kühne, Megan Stokey, Alexander Ruder, Viktor Rindert, Viktor Ivády, Igor A. Abrikosov, Chris G. Van de Walle, Mathias Schubert, and Vanya Darakchieva, Phys. Rev. B. accepted (2024)

[3] The paramagnetic Lyddane-Sachs-Teller relation, Viktor Rindert, Vanya Darakchieva, Tapati Sarkar, Mathias Schubert, arXiv:2405.15382 [cond-mat.mtrl-sci]

[4] Bloch equations in Terahertz magnetic-resonance ellipsometry, Viktor Rindert, Steffen Richter, Philipp Kühne, Alexander Ruder, Vanya Darakchieva, Mathias Schubert, arXiv:2404.12805 [cond-mat.mtrl-sci]

Author Index

Bold page numbers indicate presenter

— C —

Cobet, C.: EL1-ThA-3, 1; EL1-ThA-4, **1**

— D —

Darakchieva, V.: EL1-ThA-5, 1

— H —

Hingerl, K.: EL1-ThA-3, **1**; EL1-ThA-4, 1

— K —

Kildemo, M.: EL1-ThA-1, **1**

— R —

Rindert, V.: EL1-ThA-5, 1

Rosillo Orozco, L.: EL1-ThA-4, 1

— S —

Schiek, M.: EL1-ThA-3, 1

Schubert, M.: EL1-ThA-5, **1**

— V —

Vazquez-Miranda, S.: EL1-ThA-4, 1